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Scattering of Polarized Photons By Protons

Leonard C. Maximon

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SCATTERING OF POLARIZED PHOTONS BY PROTONS

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ABSTRACT

We derive the differential cross section for the scattering of plane polarized photons by protons below pion threshold. The contribution from the charge, spin, and anomalous magnetic moment are calculated with no approximation in the photon energy, ω. The contribution from the proton structure is included only to lowest order (viz., $O((\omega/M)^2)$), and comes from the electric and magnetic dipole polarizabilities.

I. INTRODUCTION

The determination of the electric and magnetic polarizability of the proton by the scattering of low energy photons (below pion threshold) has been of interest, both theoretically and experimentally, since the measurements of Gol'danskii <u>et al</u>., [1] in 1960. Further progress in this subject has been detailed in a number of reviews [2-4], the latest being that of Petrun'kin [5], which is both comprehensive and excellent. More recently, there has been renewed activity in view of experimental measurements with MAMI A at Mainz [6], and a number of theoretical studies have appeared, discussing relativistic effects, methods of measuring polarizabilities and quark models — L'vov [7], Petrun'kin <u>et al</u>., [8], Friar [9] and references cited therein.

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The subject is of particular concern because of the apparent conflict between the sum rule determination of the sum of the electric and magnetic dipole polarizabilities, $\bar{\alpha} + \bar{\beta}$, and the values of $\bar{\alpha}$ and $\bar{\beta}$ derived from experimental measurements of the cross section for photon scattering from the proton [10]. We comment further on this in the Summary of this article. (See also [11] and [12]). For a discussion of $\bar{\alpha}$ and $\bar{\beta}$ see [8],[9],[13],[14].

For photon energies below the pion threshold the cross section for Compton scattering from the proton is dominated by the cross section from a point particle with charge, spin, and magnetic moment equal to those of the proton. This cross section, summed over polarizations of the initial and final photons as well as over the spins of the initial and final protons, was first given by Powell [15] in the appendix of a short article; it constitutes the largest contribution to the cross section [5],[16],[17]. If, in addition, we include the contribution of lowest order in ω/M coming from the electric and magnetic dipole polarizabilities (viz., of order $(\omega/M)^2$) we have the cross section for the scattering of unpolarized photons in the lab system,

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} - \left(\frac{e^2}{Mc^2}\right)\left(\frac{\omega'}{\omega}\right)^2 \omega\omega'[\bar{\alpha}(1+\cos^2\theta) + 2\bar{\beta}\cos\theta] \tag{1}$$

where

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} = \frac{1}{2}\left(\frac{e^2}{Mc^2}\right)^2\left(\frac{\omega'}{\omega}\right)^2 \left[\begin{array}{l} \dfrac{\omega}{\omega'} + \dfrac{\omega'}{\omega} - \sin^2\theta \\ \\ + \dfrac{\omega\omega'}{M^2}\left(\begin{array}{l} 2\kappa(1-\cos\theta)^2 \\ + \kappa^2[4(1-\cos\theta) + \frac{1}{2}(1-\cos\theta)^2] \\ + \kappa^3[4(1-\cos\theta) - (1-\cos\theta)^2] \\ + \dfrac{1}{4}\kappa^4[2 + \sin^2\theta] \end{array}\right) \end{array}\right] \tag{1a}$$

is the cross section for a "point proton," given by Powell [15].

Here $\underline{k}$, $\underline{k}'$ are the momenta of the initial and final photons in the lab system

$$\begin{aligned} \omega &= |\underline{k}| \quad , \quad \omega' = |\underline{k}'| \\ \theta &= \sphericalangle\,(\underline{k},\underline{k}') \\ M &= \text{proton mass} \\ \kappa &= \text{proton anomalous magnetic moment} = 1.79 \end{aligned} \tag{2}$$

and initial and final photon energies ω and ω' are related by the Compton condition

$$\frac{\omega'}{\omega} = \frac{1}{1 + \frac{\omega}{M}\,(1-\cos\theta)} \quad . \tag{3}$$

Here and throughout this note we use Gaussian units for the electric charge, so that $e^2/\hbar c \cong 1/137$. Except for this, our notation conforms to that of Bjorken and Drell [18].

In (1) we have written the cross section in a form such that various analytic aspects are manifestly clear. The factor $(\omega'/\omega)^2$ comes from phase space and kinematical factors [18]. The remaining expression is the absolute square of the amplitude, and hence, from crossing symmetry, is invariant under the substitution $\omega \rightleftarrows -\omega'$. Further, we have written the contribution from the point particle without any approximation. On the other hand, since the terms connected with the electric and magnetic polarizabilities are relatively small corrections for these energies, only their contribution of order $(\omega/M)^2$ has been included. This comes from the cross term between the amplitude (to order $(\omega/M)^2$) connected with polarizability and the Thompson amplitude. Higher order terms, of order $(\omega/M)^4$, are given in [16] and [17]. They include contributions from the square of the dipole polarizabilities, the cross terms between the order $(\omega/M)^2$ terms in the dipole amplitudes and the order $(\omega/M)^2$ terms in the Powell cross section (1a), contributions from higher multipoles, and, most importantly, the contribution from t-channel exchange of a single neutral pion. For more detailed discussion of the importance of the π° exchange term, see [5] and [9].

In the light of proposals to make polarized photon scattering measurements using some of the high duty cycle electron accelerators currently available, we extend, in this work, the cross section (1), (1a), to include the case of plane polarized photons. The expression obtained is given in eqs. (13)-(16). Again it is written in a form having all the characteristics just described in connection with (1), (1a).

II. SCATTERING CROSS SECTION FOR POLARIZED PHOTONS

The basic expression for the amplitude for the scattering of a photon with initial and final four-momentum and polarisation k, and k', ' is given in[1] [18], p. 127 (7.67)

$$S_{fi} = \frac{1}{V^2} \sqrt{\frac{M^2}{E_f E_i}} \frac{1}{\sqrt{2\omega 2\omega'}} (2\pi)^4 \delta^4(p_f+k'-p_i-k)\mathcal{M} \tag{6}$$

where

$$\mathcal{M} = 4\pi e^2 \bar{u}(p_f,s_f) \left[(-i\not{\epsilon}') \frac{i}{\not{p}_i+\not{k}-m} (-i\not{\epsilon}) + (-i\not{\epsilon}) \frac{i}{\not{p}_i+\not{k}'-m} (-i\not{\epsilon}')\right] u(p_i,s_i) \ . \tag{7}$$

Here p_i, p_f are four-momenta of the initial and final protons with spins s_i and s_f.

In order to include the anomalous magnetic moment κ, we replace, as in [18], p.245 (10.88), the proton current $e\gamma_\mu$ by $e\Gamma_\mu$, where

$$e\Gamma_\mu = e\gamma_\mu F_1(q^2) + i\sigma_{\mu\nu} q^\nu \frac{e\kappa}{2M} F_2(q^2) \ . \tag{8}$$

Here q is the photon four momentum. Since both the initial and final photons are real, $k^2 = k'^2 = 0$, and the argument of F_1 and F_2 is zero, for which $F_1(0) = F_2(0) = 1$. We thus have

$$e\Gamma_\mu = e\gamma_\mu + i\sigma_{\mu\nu} q^\nu \frac{e\kappa}{2M} \ . \tag{8'}$$

---

[1]We have modified their expression only in that e^2 has been replaced by $4\pi e^2$, as noted following (3).

Thus we must make, in (7), the replacements

$$\not{\epsilon} \to \not{\epsilon} - \frac{\kappa}{2M} \not{\epsilon} \not{k} \qquad \text{for} \qquad q = k \tag{9}$$

$$\not{\epsilon}' \to \not{\epsilon}' - \frac{\kappa}{2M} \not{\epsilon}' \not{k}' \qquad \text{for} \qquad q = k' \tag{9a}$$

(in view of $k \cdot \epsilon = k' \cdot \epsilon' = 0$).

It should be noted that the proton current given in (8) or (8') is derived under the assumption of an on-shell vertex for a free nucleon. Thus it cannot be assumed automatically to be applicable to Compton scattering, even on a free-nucleon, since the intermediate nucleon is necessarily off-shell. We will nonetheless use the current given by (8'). For further discussion on this point we refer the reader to a recent paper by Naus and Koch [19]. We therefore substitute (9) and (9a) in (7), square, and integrate over the final proton direction as in [18], and obtain

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} = \left(\frac{\omega'}{\omega}\right)^2 |\mathcal{M}|^2 \quad . \tag{10}$$

Summing this cross section over final proton spins and averaging over initial spins by taking traces (but not over photon polarization) we obtain our final result. The algebra is carried out in the lab system ($\underline{p}_i = 0$) with the transverse gauge for the photon:

$$\begin{aligned} \epsilon &= (0, \underline{\varepsilon}) \qquad && (\underline{\varepsilon}^2 = 1) \\ \epsilon' &= (0, \underline{\varepsilon}') \qquad && (\underline{\varepsilon}'^2 = 1) \end{aligned} \quad . \tag{11}$$

Writing the result in terms of the polarizability vectors $\underline{\varepsilon}$ and $\underline{\varepsilon}'$ and the unit vectors in the direction of the photon three-momenta,

$$\underline{n} = \underline{k}/|\underline{k}| \qquad , \qquad \underline{n}' = \underline{k}'/|\underline{k}'| \tag{12}$$

we have, for the contribution from a "point proton,"

$$\left.\frac{d\sigma(\underline{\varepsilon},\underline{\varepsilon}')}{d\Omega}\right|_{\text{point}} = \frac{1}{4}\left(\frac{e^2}{Mc^2}\right)^2\left(\frac{\omega'}{\omega}\right)^2$$

$$\times\left\{\begin{aligned}&\left(\frac{\omega}{\omega'} + \frac{\omega'}{\omega} - 4(\underline{\varepsilon}\cdot\underline{\varepsilon}')^2 - 2\right)\\ &+ \frac{\omega\omega'}{M^2}\left[\begin{aligned}&4\kappa[(1-\cos\theta)^2 - ((\underline{\varepsilon}\times\underline{n})\cdot(\underline{\varepsilon}'\times\underline{n}') - \underline{\varepsilon}\cdot\underline{\varepsilon}')^2]\\ &+ \kappa^2\left[\begin{aligned}&(7-3\cos\theta)(1-\cos\theta)\\ &-(7(\underline{\varepsilon}\times\underline{n})\cdot(\underline{\varepsilon}'\times\underline{n}') - 3\underline{\varepsilon}\cdot\underline{\varepsilon}')((\underline{\varepsilon}\times\underline{n})\cdot(\underline{\varepsilon}'\times\underline{n}') - \underline{\varepsilon}\cdot\underline{\varepsilon}')\end{aligned}\right]\\ &+ 4\kappa^3\left[\begin{aligned}&(1 - \cos\theta)\\ &- (\underline{\varepsilon}\times\underline{n})\cdot(\underline{\varepsilon}'\times\underline{n}')((\underline{\varepsilon}\times\underline{n})\cdot(\underline{\varepsilon}'\times\underline{n}') - \underline{\varepsilon}\cdot\underline{\varepsilon}')\end{aligned}\right]\\ &+ \kappa^4[1 - ((\underline{\varepsilon}\times\underline{n})\cdot(\underline{\varepsilon}'\times\underline{n}'))^2]\end{aligned}\right]\end{aligned}\right\} \tag{13}$$

In deriving (13) we have made frequent use of the Compton condition (3), which may also be written in the form $M(\omega-\omega') = k\cdot k'$. We have also used the relation

$$(\underline{\varepsilon}'\cdot\underline{n})^2 + (\underline{\varepsilon}\cdot\underline{n}')^2 = 1 - (\underline{\varepsilon}\cdot\underline{\varepsilon}')^2 - (\underline{n}\cdot\underline{n}')^2 + [(\underline{\varepsilon}\times\underline{n})\cdot(\underline{\varepsilon}'\times\underline{n}')]^2 \quad . \tag{14}$$

The cross section including the contribution of lowest order in $(\omega/M)^2$ connected with the proton structure is given by the square of the amplitude for the point proton (leading to (13)) and the cross term between the $(\omega/M)^2$ terms from the dipole polarizabilities, $\bar{\alpha}$ and $\bar{\beta}$, and the Thompson amplitude. To this order, the $\bar{\alpha}$ and $\bar{\beta}$ terms do not involve the anomalous magnetic moment κ. We thus have [5]

$$\left.\frac{d\sigma(\underline{\varepsilon},\underline{\varepsilon}')}{d\Omega}\right|_{\text{dipole}} = -2\left(\frac{e^2}{Mc^2}\right)\left(\frac{\omega'}{\omega}\right)^2 \omega\omega'[\bar{\alpha}(\underline{\varepsilon}\cdot\underline{\varepsilon}')^2 + \bar{\beta}(\underline{\varepsilon}\times\underline{n})\cdot(\underline{\varepsilon}'\times\underline{n}')(\underline{\varepsilon}\cdot\underline{\varepsilon}')] \quad . \tag{15}$$

The cross section for photon scattering, not summed over either the initial or final photon polarizations is then given by (13) and (15)

$$\frac{d\sigma(\underline{\varepsilon},\underline{\varepsilon}')}{d\Omega} = \left.\frac{d\sigma(\underline{\varepsilon},\underline{\varepsilon}')}{d\Omega}\right|_{\text{point}} + \left.\frac{d\sigma(\underline{\varepsilon},\underline{\varepsilon}')}{d\Omega}\right|_{\text{dipole}} \tag{16}$$

If the polarization of the final photon is not observed, then the cross section (16) should be summed over $\underline{\varepsilon}'$. The sums are all of the form

$$\sum_{\underline{\varepsilon}'}(\underline{a}\cdot\underline{\varepsilon}')(\underline{b}\cdot\underline{\varepsilon}') = \underline{a}\cdot\underline{b} - (\underline{a}\cdot\underline{n}')(\underline{b}\cdot\underline{n}') \quad . \tag{17}$$

For the point cross section we obtain

$$\left.\frac{d\sigma(\underline{\varepsilon})}{d\Omega}\right|_{\text{point}} = \tfrac{1}{2}\left(\frac{e^2}{Mc^2}\right)^2\left(\frac{\omega'}{\omega}\right)^2 \left\{ \begin{array}{l} \left(\frac{\omega}{\omega'} + \frac{\omega'}{\omega} - 2(\underline{\varepsilon}\cdot\underline{n}')^2\right) \\ + \frac{\omega\omega'}{M^2} \left[\begin{array}{l} 2\kappa(1-\cos\theta)^2 \\ + \kappa^2[5(1-\cos\theta) + \tfrac{1}{2}\sin^2\theta - 2(\underline{\varepsilon}\cdot\underline{n}')^2] \\ + \kappa^3[2(1-\cos\theta) + 2\sin^2\theta - 2(\underline{\varepsilon}\cdot\underline{n}')^2] \\ + \frac{1}{2}\kappa^4[1 + \sin^2\theta - (\underline{\varepsilon}\cdot\underline{n}')^2] \end{array} \right] \end{array} \right\} \quad (18)$$

The contribution from the dipole polarizabilities, summed over final photon polarization, is, from (15) and (17),

$$\left.\frac{d\sigma(\underline{\varepsilon})}{d\Omega}\right|_{\text{dipole}} = -2\left(\frac{e^2}{Mc^2}\right)\left(\frac{\omega'}{\omega}\right)^2 \omega\omega'[\bar{\alpha}(1-(\underline{\varepsilon}\cdot\underline{n}')^2) + \bar{\beta}\ \underline{n}\cdot\underline{n}'] \quad . \qquad (19)$$

(Note here that $\bar{\alpha}$ and $\bar{\beta}$ have the dimensions of L^3; the dimension of $\omega\omega'$ should therefore be taken to be $1/L^2$.)

The cross section for the scattering of plane polarized photons, summed over final polarizations is then given by (18) and (19):

$$\frac{d\sigma(\underline{\varepsilon})}{d\Omega} = \left.\frac{d\sigma(\underline{\varepsilon})}{d\Omega}\right|_{\text{point}} + \left.\frac{d\sigma(\underline{\varepsilon})}{d\Omega}\right|_{\text{dipole}} \qquad (20)$$

Finally, defining the scattering cross sections for photons with initial polarization perpendicular to and parallel to the photon scattering plane, $d\sigma_{\perp}/d\Omega$ and $d\sigma_{\parallel}/d\Omega$, we have from (18)-(20),

$$\frac{d\sigma_{\perp}}{d\Omega} = \tfrac{1}{2}\left(\frac{e^2}{Mc^2}\right)^2\left(\frac{\omega'}{\omega}\right)^2 \left\{ \begin{aligned} &\left(\frac{\omega}{\omega'} + \frac{\omega'}{\omega}\right) \\ &+ \frac{\omega\omega'}{M^2}\left[\begin{aligned} &2\kappa(1-\cos\theta)^2 \\ &+ \kappa^2[5(1-\cos\theta) + \tfrac{1}{2}\sin^2\theta] \\ &+ \kappa^3[2(1-\cos\theta) + 2\sin^2\theta] \\ &+ \tfrac{1}{2}\kappa^4[1 + \sin^2\theta] \end{aligned}\right] \end{aligned} \right\} \tag{21}$$

$$- \left(\frac{e^2}{Mc^2}\right)\left(\frac{\omega'}{\omega}\right)^2 \omega\omega'\{2\bar{\alpha} + 2\bar{\beta}\cos\theta\}$$

and

$$\frac{d\sigma_{\parallel}}{d\Omega} = \tfrac{1}{2}\left(\frac{e^2}{Mc^2}\right)^2\left(\frac{\omega'}{\omega}\right)^2 \left\{ \begin{aligned} &\left(\frac{\omega}{\omega'} + \frac{\omega'}{\omega} - 2\sin^2\theta\right) \\ &+ \frac{\omega\omega'}{M^2}\left[\begin{aligned} &2\kappa(1-\cos\theta)^2 \\ &+ \kappa^2[5(1-\cos\theta) - \tfrac{3}{2}\sin^2\theta] \\ &+ \kappa^3[2(1-\cos\theta)] \\ &+ \tfrac{1}{2}\kappa^4 \end{aligned}\right] \end{aligned} \right\} \tag{22}$$

$$- \left(\frac{e^2}{Mc^2}\right)\left(\frac{\omega'}{\omega}\right)^2 \omega\omega'\{2\bar{\alpha}\cos^2\theta + 2\bar{\beta}\cos\theta\} \quad .$$

As can be seen either from these expressions or directly from (18), the difference does not depend on the magnetic polarizability:

$$\frac{d\sigma_\perp}{d\Omega} - \frac{d\sigma_\parallel}{d\Omega} = \left(\frac{e^2}{Mc^2}\right)^2 \left(\frac{\omega'}{\omega}\right)^2 \left[1 + \frac{2\omega\omega'}{M^2} \kappa^2 (1 + \frac{1}{2}\kappa)^2\right] \sin^2\theta$$

$$-2 \left(\frac{e^2}{Mc^2}\right) \left(\frac{\omega'}{\omega}\right)^2 \omega\omega' \bar{\alpha} \sin^2\theta \quad . \tag{23}$$

III. SUMMARY

A number of observations which may help provide a guide for experimental measurements using plane polarized photons follow from eq. (21), (22), and (23). First, from eq. (23) it is obvious that the cross sections $d\sigma_\perp/d\Omega$ and $d\sigma_\parallel/d\Omega$ are equal for forward and backward scattering ($\theta = 0°$ and $\theta = 180°$) (see Fig. 1). Therefore, if Compton scattering of polarized photons is to be used to determine the electric polarizability, $\bar{\alpha}$, scattering angles in the region near 90° should be chosen. Moreover, we note from eqs. (21) and (22) that at $\theta = 90°$, the cross section $d\sigma_\parallel/d\Omega$ is independent of both $\bar{\alpha}$ and $\bar{\beta}$; only the cross section for the "point proton" remains (see Fig. 1). Thus, separate measurements of $d\sigma_\parallel/d\Omega$ and $d\sigma_\perp/d\Omega$ at 90° could provide both a check of the validity of neglecting $(\omega/M)^4$ terms by comparison of the measured $d\sigma_\parallel/d\Omega$ with eq. (22), and a determination of $\bar{\alpha}$ by comparison of $d\sigma_\perp/d\Omega$ with eq. (23). (We note that the maximum value of $d\sigma_\perp/d\Omega - d\sigma_\parallel/d\Omega$ does not occur at precisely 90° since ω' is a function of θ, as given in eq. (3).)

Second, looking at the terms in $\bar{\alpha}$ and $\bar{\beta}$ in eqs. (21) and (22), one sees that, in the forward direction, each of the cross sections, $d\sigma_\perp/d\Omega$ and $d\sigma_\parallel/d\Omega$, depends on $\bar{\alpha}$ and $\bar{\beta}$ only in the form of the sum $\bar{\alpha} + \bar{\beta}$. Therefore, if one considers the sum of the dipole polarizabilities to be fixed by the sum rule [9], [20],

$$\bar{\alpha} + \bar{\beta} = \frac{1}{2\pi^2} \int_{\omega_0}^{\infty} \frac{\sigma_{tot}(\omega)d\omega}{\omega^2} \tag{24}$$

then it follows that one must make measurements for angles $\theta \gtrsim 90°$ in order to determine the individual values of $\bar{\alpha}$ and $\bar{\beta}$. This may be seen for the cross section for unpolarized photons shown in Fig. 4 of [9] and in Fig. 1 of this article for the cross sections for polarized photons. Thus for both of these reasons, measurements of $d\sigma_{\parallel}/d\Omega$ and $d\sigma_{\perp}/d\Omega$ with polarized photons would appear to be most useful in the region $\theta \gtrsim 90°$.

Although a measurement of the difference of the cross sections, given in eq. (23), is of special interest in that it depends only on $\bar{\alpha}$, the asymmetry,

$$A(\omega,\theta) = \frac{d\sigma_{\perp} - d\sigma_{\parallel}}{d\sigma_{\perp} + d\sigma_{\parallel}} \tag{25}$$

is often of preferred experimentally since many of the experimental uncertainties cancel. In Fig. 2 we plot $A(\omega,\theta)$ as a function of the scattering angle for a number of values of $\bar{\beta}$, with fixed $\bar{\alpha} + \bar{\beta}$. It should be noticed there that in the region of large asymmetry, $60° < \theta < 110°$, a change from $\bar{\beta} = 0$ to $\bar{\beta} = 2 \times 10^{-4}$ fm^3, produces at most a 6% change in the asymmetry.

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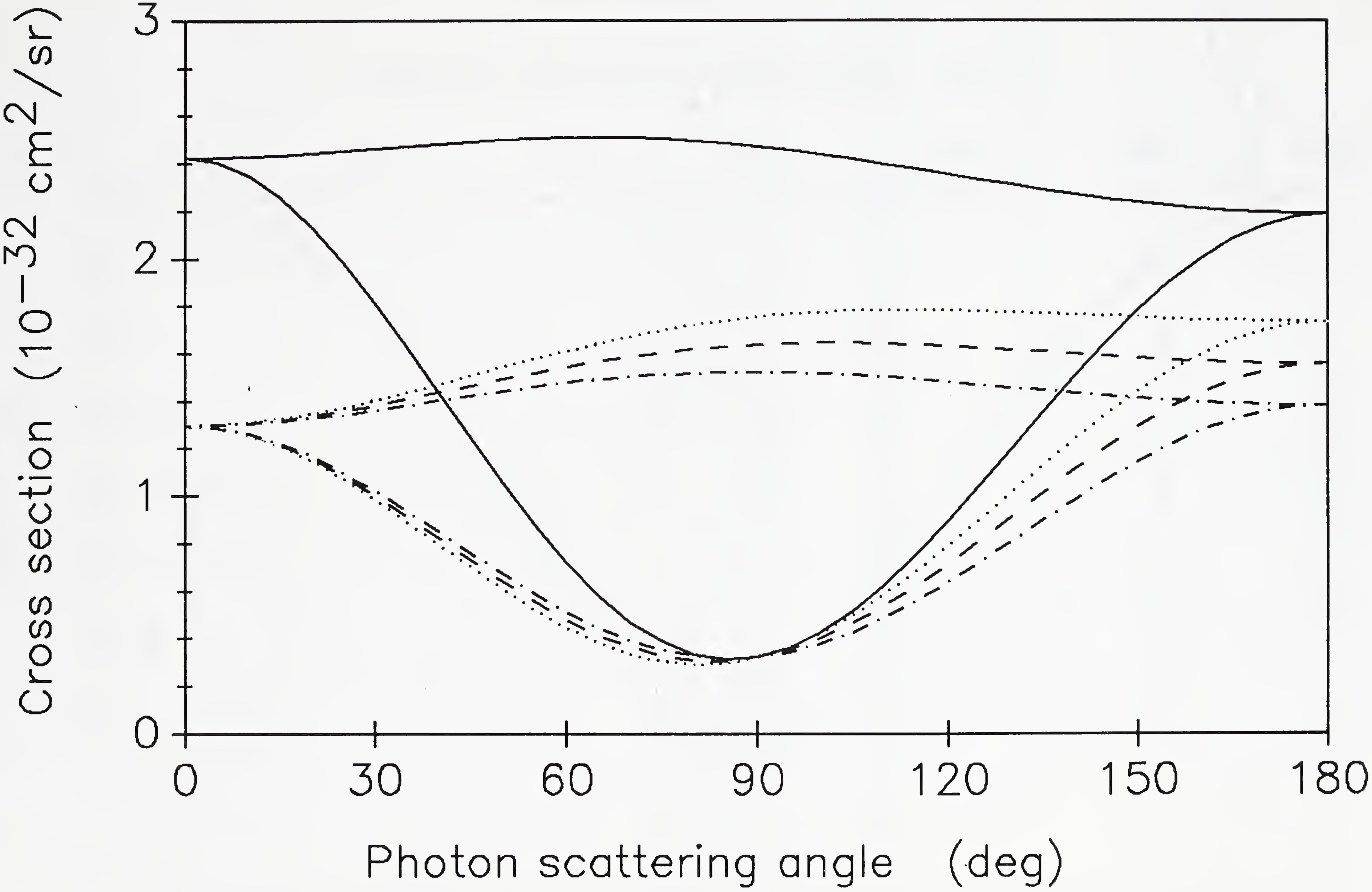
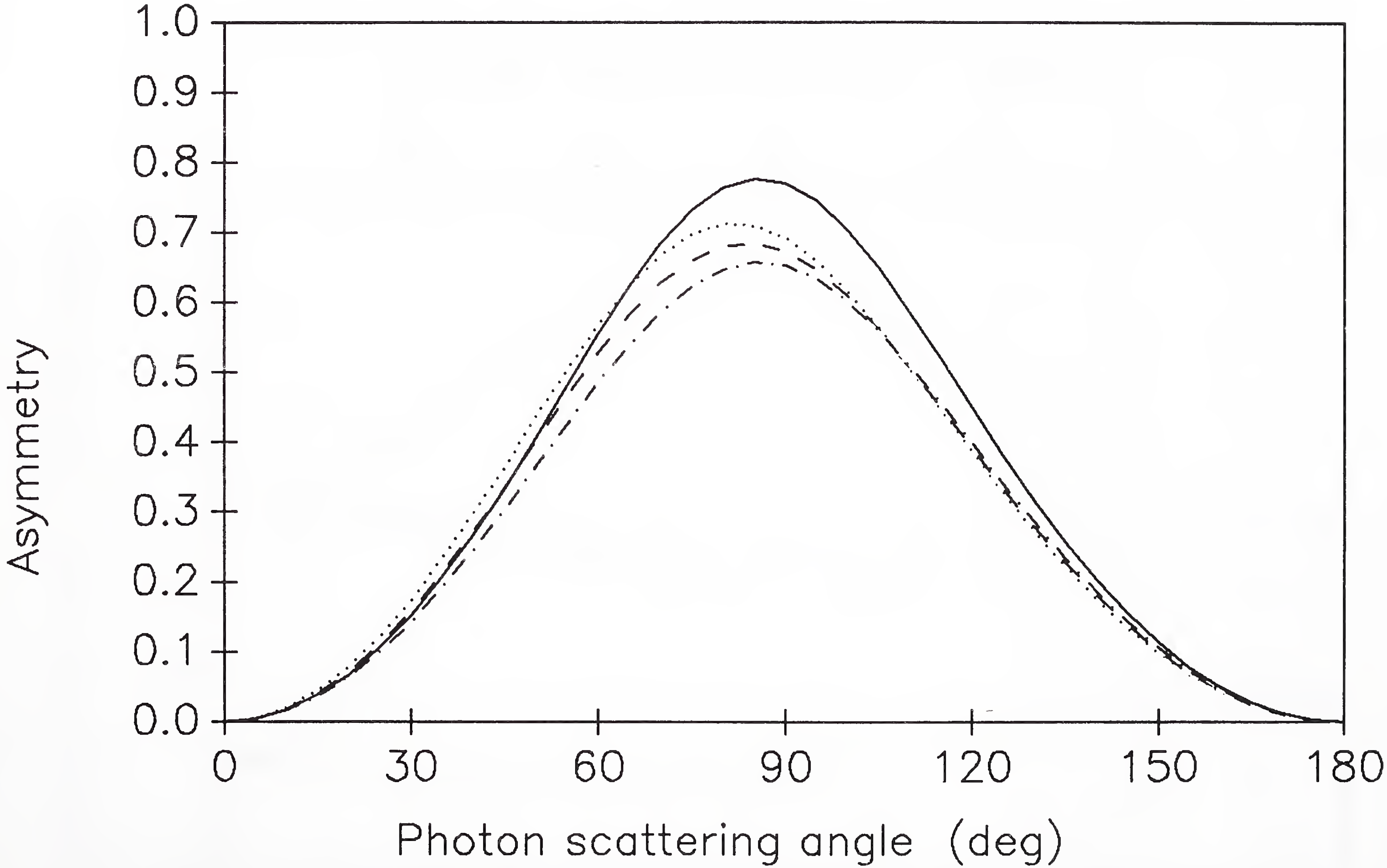
FIGURE CAPTIONS

Fig. 1. Cross sections $d\sigma_\perp/d\Omega$ and $d\sigma_\parallel/d\Omega$ plotted as a function of photon scattering angle, for an incident photon energy $\omega = 100$ MeV. The relatively flat curves all pertain to $d\sigma_\perp/d\Omega$; the curves with a pronounced dip all pertain to $d\sigma_\parallel/d\Omega$. The solid curves are for $\bar{\alpha} = \bar{\beta} = 0$. The remaining curves all have $\bar{\alpha} + \bar{\beta} = 14.3 \times 10^{-4}$ fm^3. Dotted curves have $\bar{\beta} = 2 \times 10^{-4}$ fm^3, long dashed curves have $\bar{\beta} = 0$; dash-dot curves have $\bar{\beta} = 2 \times 10^{-4}$ fm^3.

Fig. 2. Asymmetry $A(\omega,\theta)$ plotted as a function of photon scattering angle, for an incident photon energy $\omega = 100$ MeV. The solid curve is for $\bar{\alpha} = \bar{\beta} = 0$. The remaining curves all have $\bar{\alpha} + \bar{\beta} = 14.3 \times 10^{-4}$ fm^3. Dotted curve has $\bar{\beta} = 2 \times 10^{-4}$ fm^3, long dashed curve has $\bar{\beta} = 0$; dash-dot curve has $\bar{\beta} = 2 \times 10^{-4}$ fm^3.



Cross section (10−32 cm2/sr)
3
2
1
0
0
30
60
90
120
150
180
Photon scattering angle (deg)


Asymmetry
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
30
60
90
120
150
180
Photon scattering angle (deg)

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6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

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10. SUPPLEMENTARY NOTES

__ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

We derive the differential cross section for the scattering of plane polarized photons by protons below pion threshold. The contribution from the charge, spin, and anomalous magnetic moment are calculated with no approximation in the photon energy, ω. The contribution from the proton structure is included only to lowest order (viz., $O((\omega/M)^2)$), and comes from the electric and magnetic dipole polarizabilities.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

electromagnetic interaction of protons; photon-proton scattering; polarized photons; proton anomalous moment; proton Compton scattering; proton dipole polarizabilities

13. AVAILABILITY

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